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Discovery of epidosites in the Mount Ślęża ophiolite (Fore-Sudetic Block, SW Poland)

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The first suite of epidosite from the Central Sudetic Ophiolites has been discovered in the sheeted dyke complex of the Mount Ślęża ophiolite (SW Poland). Epidosites from the Mount Ślęża ophiolite represent A-type epidosites which metasomatically replaced diabasic sheeted dykes of the Strzegomiany–Kunów Fe-Ti mineralisation zone. They form decimetre-scale elongated pistachio-green patches or veins within single dykes. Their composition (quartz + epidote + titanite) is analogue to Troodos ophiolite end-member epidosite of Cyprus. The pistacite content of epidote range from Ps_{16} to Ps_{31} and is similar to those from other ophiolitic epidosites. Titanite is low in Al_2O_3 (0.61 to 1.10 wt.%) and Fe_2O_3 (0.43 to 0.63 wt.%) and high in V_2O_5 (from 0.22 to 0.47 wt.%). The presence of epidosites in the Mount Ślęża ophiolite can be considered as an evidence of its supra-subduction zone (SSZ) affinity. Finally, a direct link between the epidosite formation and the release of base metals from its protolith (Cu, Zn and Co) indicates the possibility of the Cyprus-type volcanogenic massive sulphide deposit (VMS) formation in the Mount Ślęża ophiolite.

Key words: epidosites, Mount Ślęża ophiolite, black smokers, hydrothermal alteration.

INTRODUCTION

Epidosites are characterized by metasomatic replacement of primary igneous minerals by granoblastic assemblages of quartz + epidote ± titanite ± chlorite ± actinolite (Alt, 1995; Banerjee et al., 2000; Tivey, 2007; Jowitt et al., 2012). In the field, epidosites have a spectacular pistachio-green colour. Petrological, geochemical, isotopic and field data suggest that they form in the upflow zones at the base of active ore-forming oceanic hydrothermal systems that vent as a black smoker on the ocean-floor (Nehlig et al., 1994; Alt, 1995; Banerjee et al., 2000; Pirajno, 2009). Epidosites are localized below large massive sulphide deposits forming the deep upwelling feeder zones for the deposits (Alt, 1995). As a result, detection of epidosites may be a useful tool for the prospection of ophiolite-related VMS deposits (Jowitt et al., 2007). Epidosites are found in many supra-subduction zone ophiolites, including Troodos (Jowitt, 2012), Samail (Nehlig et al., 1994) and Josephine (Harper, 1995), as well as in modern supra-subduction-related environments (e.g., Tonga forearc, Banerjee et al., 2000). Similarities between both modern and ancient epidosites and their absence in the mid-ocean ridge record indicate that tectonic setting is an important factor controlling the formation of epidosites.

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In this paper we report on newly discovered epidosites from the sheeted dyke complex of the Mount Ślęża ophiolite that represents the first documented suite from the Central Sudetic Ophiolites. Petrological, geochemical, mineralogical and microprobe data are used for a brief description of these peculiar rocks.

OPHIOLITE-RELATED EPIDOSITE TYPES

Ophiolitic epidosites typically occur within the lower half of basaltic sheeted dykes (type A) and plagiogranitic bodies (type B) (Banerjee et al., 2000). Within basaltic sheeted dyke complexes, epidosites form patches or stripes within a single dyke (Nehlig et al., 1994) or compose large zones (as much as hundreds of metres) of completely recrystallised dykes (Philips-Lander and Dilek, 2009). Plagiogranite-hosted epidosites occur as irregular patches up to a few metres wide (Banerjee et al., 2000). Continental-crustal, skarn-related epidosites (e.g., central Bohemian Vlastějovice skarn; Vrána and Frýda, 2003) are not the subject of this paper.

On the basis of secondary mineralogy, Jowitt et al. (2012) divided the well-developed epidosite zone of Spillia-Kanavia from the Troodos ophiolite sheeted dyke complex into four facies. In order of decreasing modal amphibole and increasing modal epidote, these are:

– diabase;
– transitional diabase–epidosite;
– intermediate epidosite;
– end-member epidosite.

Diabase is made up of amphibole + albitic plagioclase + chlorite ± epidote ± quartz ± Fe-Ti oxides ± titanite and retains an igneous texture. Ilmenite is partly replaced by titanite. Transitional diabase-epidosite contains the same mineral assemblage as diabase, but abundance of chlorite (>30%), quartz (15–30%) and epidote (15–30%) is considerably higher. This alteration facies lacks an igneous texture. Intermediate epidosite is made up of epidote (>30%), quartz (>30%) and chlorite (15–30%) with no relics of igneous textures. Finally, end-member epidosite consists almost entirely of epidote (up to 63%) and quartz with minor chlorite (up to 10%). Accessory titanite occurs through all the facies, but is more abundant in epidote-rich lithologies (especially end-member epidosite).

GEOLOGICAL SETTING

The Central Sudetic Ophiolites (Mount Ślęża ophiolite, Szklary Massif, Nowa Ruda Massif, and Braszowice–Brzeźnica Massif) are ca. 400 Ma (Olivier et al., 1993; Dubińska et al., 2004; Kryza and Pin, 2010), relatively well-preserved ophiolitic suites delineate likely major Sudetic tectonic sutures. These large ultramafic-mafic complexes are among the best-preserved and complete ophiolitic sequences in the Variscan Belt (Kryza and Pin, 2010). The largest of the Central Sudetic Ophiolites, the Mount Ślęża ophiolite (named by Majerowicz, 1979), has preserved a complete ophiolite pseudostratigraphic sequence (see Floyd et al., 2002 and references therein). From south to north (bottom to top) the Mount Ślęża ophiolite comprises: serpentitised and tectonised peridotites, pyroxene- and amphibole-rich rocks (ultramafic cumulates), metagabbros (predominantly mafic cumulates) of the Mount Ślęża Massif, sheeted dykes and lavas (with rare pillowed basalts) and finally dark radiolaria-bearing metacherts (pelagic sedimentary cover). Apart from the basic members, small bodies of rodingites and plagiogranites are found (Dubińska and Gunia, 1997; Kryza, 2011). Finally, the age of granitic veins of continental-crustal affinity (ca. 337 Ma) crosscutting the ultramafic member of the Mount Ślęża ophiolite indicates the probable minimal age of obduction (Kryza, 2011).

The Mount Ślęża ophiolite is characterized by a distinct geochemical contrast between plutonic and subvolcanic/volcanic members. The latter represents more evolved magmas [MgO/(MgO + FeO) = 0.27–0.30 compared with plutonic MgO/(MgO + FeO) = 0.50–0.75] with relatively higher concentrations of Fe, Ti, V, P and other incompatible elements (Kryza and Pin, 2010). According to the classification diagram of Winchester and Floyd the subvolcanic/volcanic member can be classified as andesites (Kryza and Pin, 2010). In the field the discriminative feature of the subvolcanic/volcanic member is abundance of Fe-Ti oxides (up to 30% of ilmenite).

Metamorphic and structural development of the ophiolite suite inferred from ultramafic rocks, associated rodingites (Dubińska and Gunia, 1997) and metagabbros (Majerowicz et al., 2000; Jędrysek et al., 2000) refers to the typical sequence of oceanic and subsequent continental metamorphic events.

PETROGRAPHY

EPIDOSITE

Epidosite suite is exposed in a sheeted dyke complex outcrop located 380 m a.s.l. within a morphological ridge that delineates the strike of the Strzegomiany–Kunów mineralisation zone (Fig. 1). Only A-type epidosites are present in the Mount Ślęża ophiolite collection. Discovered epidosites are preserved as patches or relatively thin (<5 cm) veins within a single dyke. All of the collected epidosite samples have a distinctive green colour contrasting with dark greenish-grey metadiabase (protholite).

The mineral assemblage of epidosites from the Mount Ślęża ophiolite is analogous to end-member epidosite from Cyprus (Jowitt et al., 2012). They are characterized by the metasomatic replacement of igneous textures and minerals by fine- to medium-grained granoblastic assemblages of quartz + epidote + titanite (Fig. 2). Accessory phases, where present, include amphibole and ilmenite disseminated in quartz-epidote matrix. The former occurs as fine acicular crystals (Fig. 3). The latter shows skeletal textures (relics after dissolved titanomagnetite) and is commonly replaced by titanite. Degree of ilmenite alteration varies from partial (rims encircling Fe-Ti oxide grains) to complete replacement (Figs. 4 and 5). Ilmenite is likely the only relic of primary, igneous mineral assemblage. Lack of chlorite in the collected rock material is symptomatic for the most altered epidosite suites (Jowitt et al., 2012).

No voids or vesicles were observed, nevertheless bimodal grain-size distribution of quartz and epidote indicates possibility of pore-filling growth of metasomatic phases. A fine-grained (avg. 20 μm), turbid, anhedral population of quartz and epidote appears to have grown as a groundmass replacement. Medium-grained (avg. 250 μm), clear, anhedral to prismatic grains of quartz and epidote are typical for growth in pore space (Banerjee et al., 2000). Fluid inclusions are ubiquitous through both populations.

The contact between end-member epidosite and protholite (diabase *sensu* Jowitt et al., 2012) is sharp (Fig. 6). No transition facies (intermediate epidosite or transitional diabase-epidosite) were observed.

PROTHOLITE

Epidosite protholite is greenish-grey, fine grained metadolerite that have preserved evident relic igneous texture (Fig. 7). Primary plagioclase (30%) is replaced by granular albite–andesine (Majerowicz and Pin, 1994) and green amphibole in the form of acicular aggregates. Primary pyroxene is completely replaced by felted masses of green to pale green amphibole (30%). No relics of pyroxene were observed. Ilmenite laths (30%) form skeletal relics after partially dissolved titanomagnetite. Space left after magnetite is completely filled with assemblage of secondary plagioclase + green amphibole. Minor relics of martitised magnetite occupy inner parts of titanomagnetite relics (Fig. 7), in the proximity of epidosite, ilmenite is rimmed by titanite. Accessory phases include chlorite, epidote, sulphides (pyrite, pyrrhotite and chalcopyrite) and quartz.

The isotopic mass-balance of sulphur suggests that at least 20% of total sulphur in the Mount Ślęża ophiolite subvolcanic/volcanic member was assimilated from sea water. The rest of sulphur (80%) is of magmatic origin (Jędrysek et al., 2000). Significant magmatic SO_2 inputs have been described from seamounts and arc-related settings (Sedwick et al, 1992). Importance of such inputs in the mid-ocean ridge (MOR) hydrothermal system is not known (Alt, 1995).

The metamorphic mineral assemblage and textures are typical for greenschist facies of sheeted dyke complexes (Heft et al., 2008). Petrological evidence is supported by sulphur isotope ratios. The temperature obtained for the chalcopyrite–pyrrhotite pair yielded is about 450°C (Jędrysek et al., 2000). In terms of Jowitt et al. (2012), protholite of Mount Ślęża ophiolite epidosites is analogous to diabase facies of the Spillia–Kanavia epidosite zone.

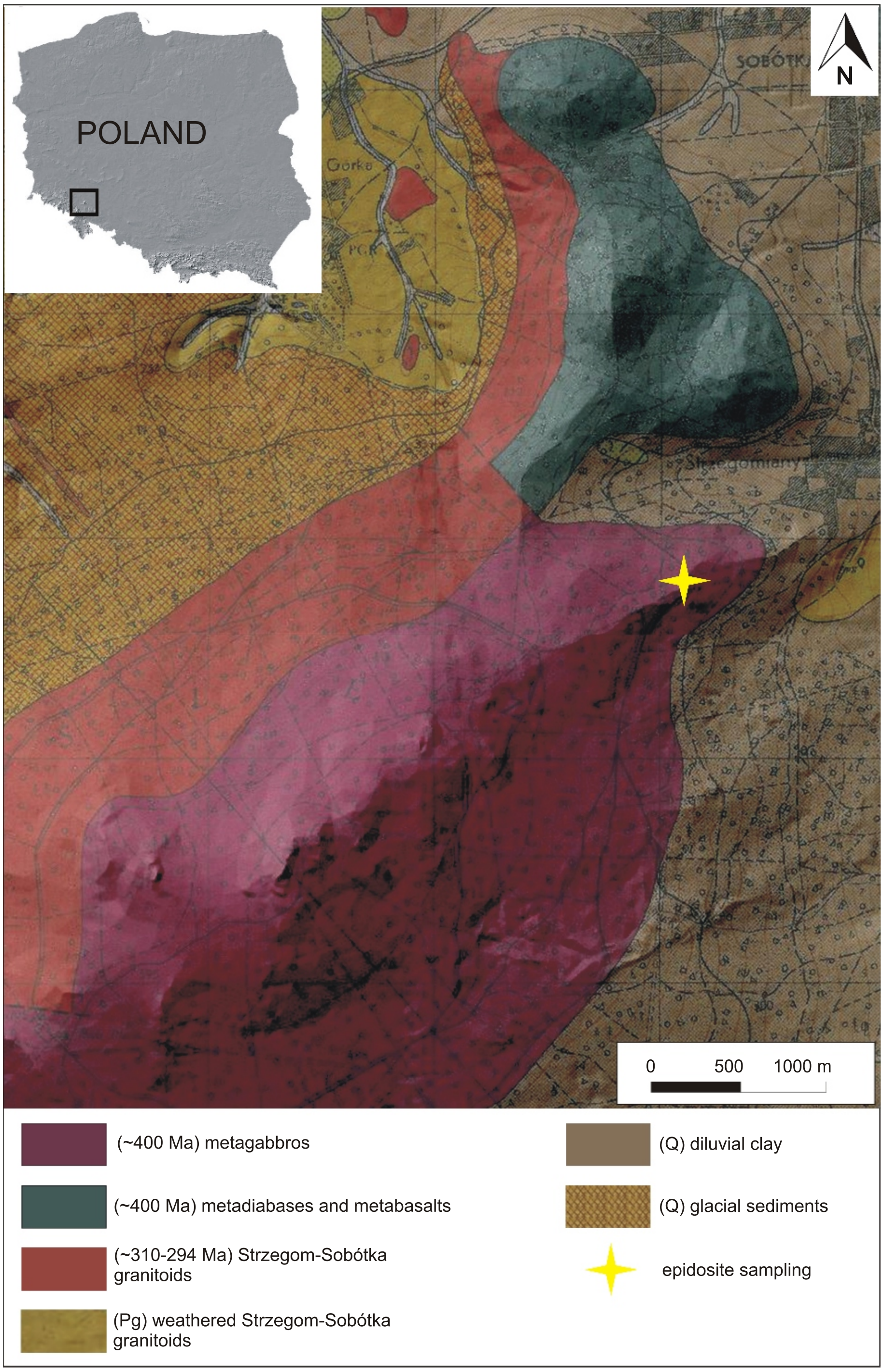

Fig. 1. Geological map of the Mount Ślęża area (plutonic, subvolcanic and volcanic members of the ophiolite sequence (modified from Gaździk, 1957)

MINERAL CHEMISTRY

Electron-microprobe analyses of epidote and titanite were carried out at the Faculty of Geology of Warsaw University with a *Camexa SX100*. The analyses were done using a focused beam, the accelerating voltage and current of the focused beam being 15 keV and 20 nA, respectively.

Representative analyses of titanite are given in Appendix 1*. The Al_2O_3 and Fe_2O_3 contents range from 0.61 to 1.10 wt.% and from 0.43 to 0.63 wt.%, respectively. The titanite also shows a minor F content (from 0.00 to 0.22 wt.%) and trace

* Supplementary data associated with this article can be found, in the online version, at doi: 10.7306/gq.1317

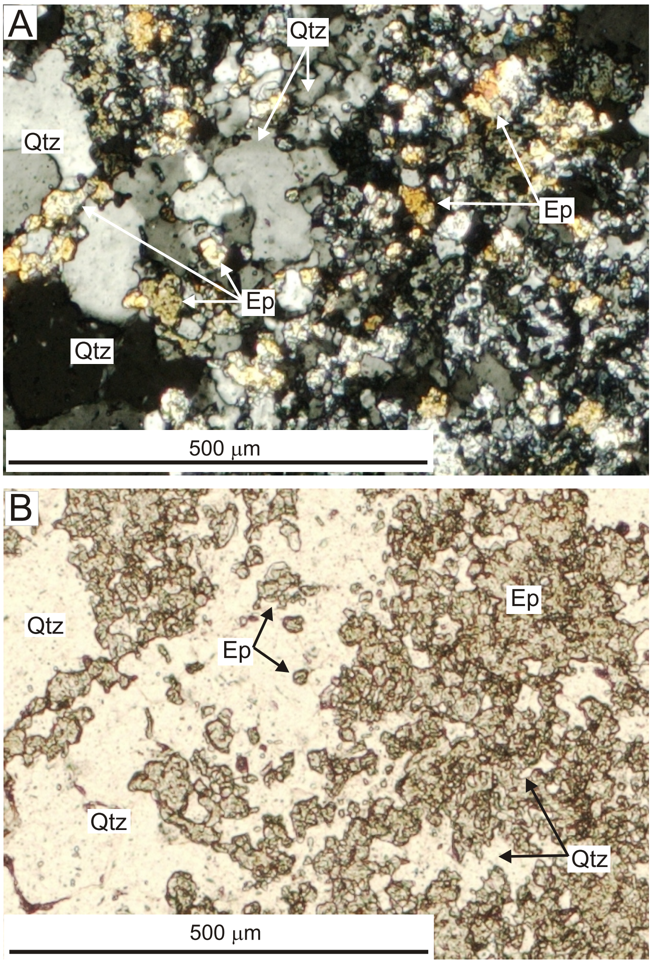

Fig. 2. Photomicrograph of the Mount Ślęża ophiolite end-member epidosite characterized by granoblastic assemblage of clear and turbid quartz (Qtz) + epidote (Ep)

A – transmitted XPL light, B – transmitted PPL light

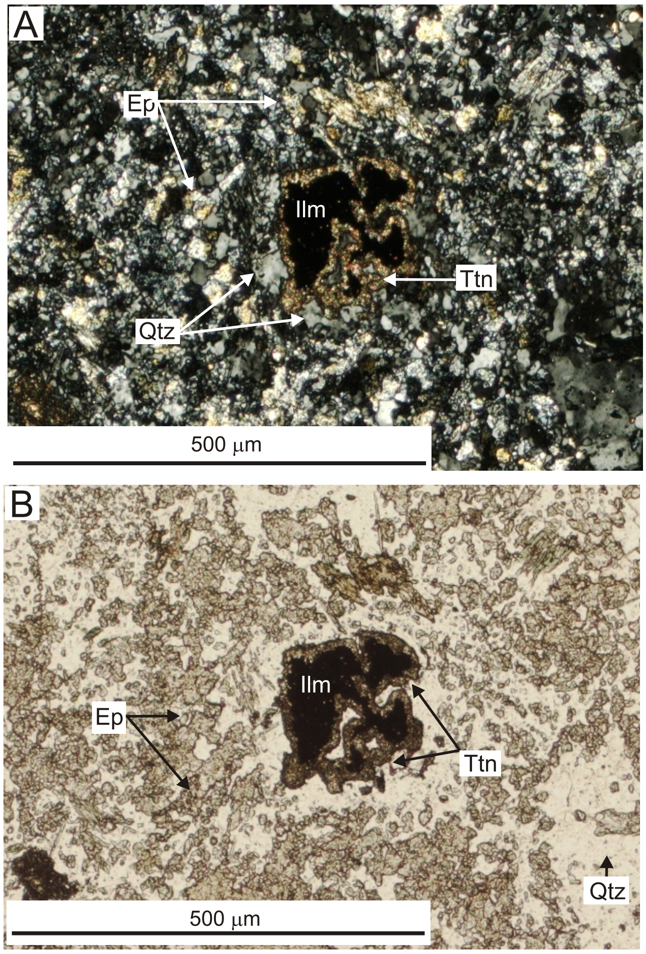

Fig. 4. Photomicrograph of the Mount Ślęża ophiolite end-member epidosite with relic of primary igneous ilmenite (Ilm) rimmed by titanite (Ttn)

Ilmenite grains are randomly disseminated in quartz (Qtz) + + epidote (Ep) matrix; A – transmitted XPL light, B – transmitted PPL light

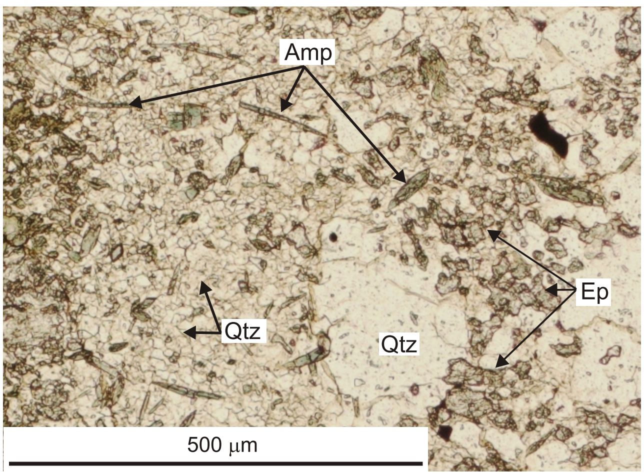

Fig. 3. Photomicrograph of the Ślęża ophiolite end-member epidosite (Qtz + Ep) with accessory acicular amphibole (Amp)

Transmitted PPL light

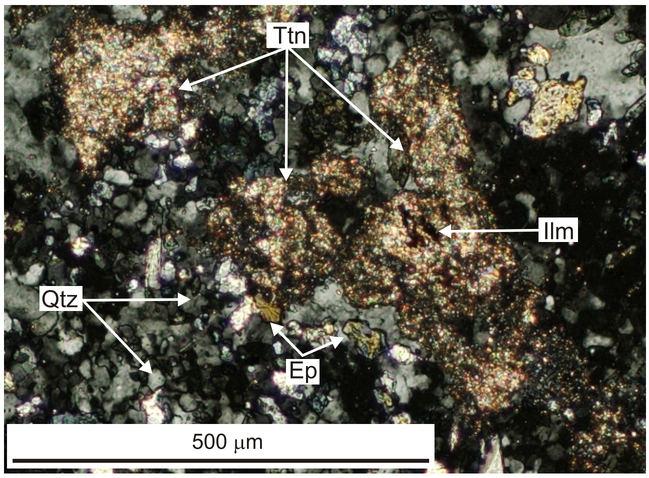

Fig. 5. Photomicrograph of ilmenite (Ilm) grain almost completely replaced by titanite (Ttn)

Transmitted XPL light

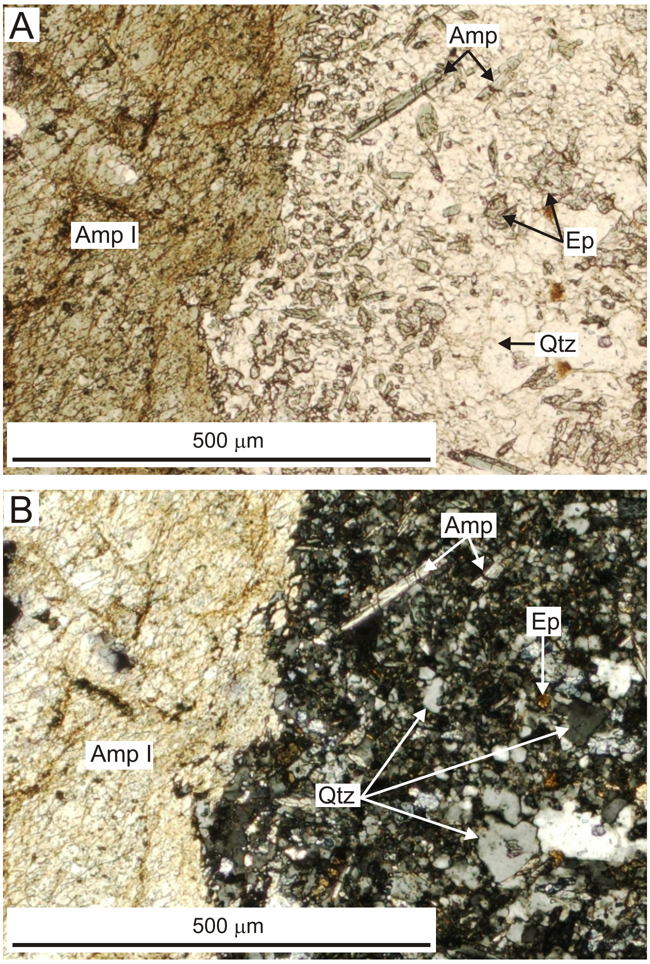

Fig. 6. Photomicrograph of contact between end-member epidosite (Qtz + Ep + Amp) and protholite rock-forming amphibole (Amp I); note sharp character of contact

A – transmitted XPL light, B – transmitted PPL light

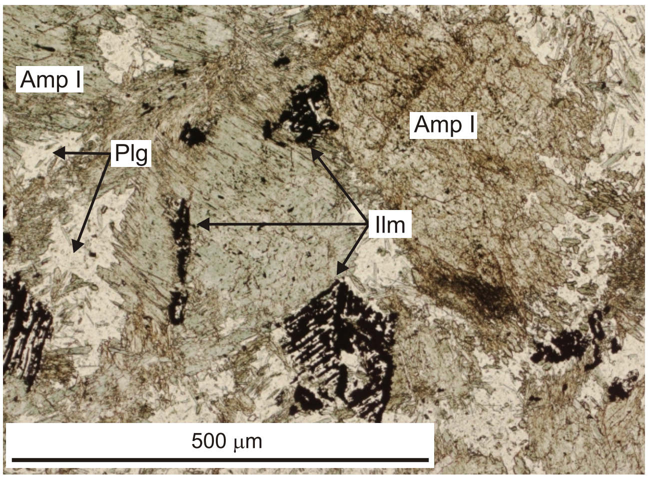

Fig. 7. Photomicrograph of protholite metadiabase composed of rock-forming amphibole (Amp I), plagioclase (Plg) and ilmenite relics after titanomagnetite (Ilm)

Note preservation of igneous texture and lack of magmatic pyroxene; transmitted XPL light

of Cl (max. 0.001 wt.%). Unusual and high V_2O_5 content (from 0.22 to 0.47 wt.%) can be considered as a function of the titanomagnetite composition (up to 1.9 wt.% V_2O_5 in magnetite, author's unpublished data) and the fluid – titanite partition coefficient. The titanite shows some Al + Fe^{3+} excess over F, which indicates the operation of additional Al-involving substitution reactions (René, 2011). No obvious zonation and significant variations in the chemical composition were observed.

Representative composition of residual ilmenite is given in Appendix 2. The analysed ilmenite has a very low amount of pyrophanite ($MnTiO_3$, MnO up to 1.70 wt.%) and geikelite ($MgTiO_3$, MgO up to 0.054 wt.%) components. The amount of hematite component is also negligible (Fe_2O_3 content up to 1.057 wt.%).

Representative analysis of epidote are given in Appendix 3. The content of pistacite [Ps, $Ca_2Fe_3Si_3O_{12}(OH)$ end member] in epidote ranges from Ps_{16} to Ps_{31}, with the average of Ps_{24}. The contents of REE in the titanite are under the detection limit of microprobe analysis.

SIGNIFICANCE OF EPIDOSITES IN OPHIOLITIC SUITES

Formation of epidosites is broadly considered as one of the most crucial subsea-floor processes in the mid-ocean ridge hydrothermal systems (Alt, 1995). At the base of an active, mid-ocean ridge hydrothermal system, the so-called reaction zone (340–465°C and 350–550 bars; Von Damm, 1990) where conditions are close to the critical point for sea water (Bischoff and Rosenbauer, 1985), the physical properties of hydrothermal fluids change drastically. When critical conditions are approached, the density and the viscosity of fluids reach their minima while the coefficient of thermal expansion and the heat capacity reach their maxima. These factors combine to limit further heating of hydrothermal fluids and promote rapid upflow of evolved (i.a., acidic, anoxic, Ca-enriched, Mg-depleted and base-metal rich) hydrothermal solutions (Alt, 1995). Upflow zones of the oceanic hydrothermal system can be classified as diffusive and focused (Alt, 1995). Diffusive upflow zones do not channel fluids directly onto the ocean-floor (i.e. hydrothermal fluids mix with near-ambient sea water of the uppermost crustal aquifer). Focused upflow zones sufficiently channel high temperature fluids to vent directly onto the sea-floor as black smokers (e.g., Fornari and Embley, 1995).

Deep, focused hydrothermal upflow zones of ophiolites (lowermost sheeted dyke or sheeted dyke-gabbro transition hosted) are characterized by epidosites (Nehlig et al., 1994; Alt, 1995). Epidosites are localized below large VMS sulphide deposits, forming the deep upwelling feeder zones for the deposit (Nehlig et al., 1994; Varga et al., 1999; Jowitt et al., 2012). In well-preserved ophiolites (e.g., Samail; Nehlig et al., 1994), focused upflow zones are inferred to extend upward from epidosites into zones of quartz + epidote veins, which can then be traced to quartz + sulphide ± epidote veins and argillic alteration beneath shallow stockwork feeder zones for massive sulphide deposits. A detailed study of base metal (Cu, Zn, Mn, Ni and Co) leaching from epidosites of Troodos ophiolite (Jowitt et al., 2012) plausibly characterized a direct link between the epidosite formation and the release of base metals into the ore-forming oceanic hydrothermal system.

Theoretical studies suggest that epidosites should exist at mid-ocean ridges (Seyfried et al., 1988), but they are conspicuously rare in the rock record from modern oceanic settings (Banerjee et al., 2000). In contrast, epidosites comprise several per cent of the sheeted dyke complexes in ophiolites (Alt, 1995). The lack of these peculiar rocks from the modern oceanic settings can be interpreted as a fundamental difference between the oceanic and ophiolitic crust. The first well-documented and modern epidosite suites were recovered from the Tonga forearc (Banerjee and Gills, 2001). Tongan forearc epidosites formed under conditions similar to many supra-subduction zone (SSZ) ophiolites (e.g., Troodos, Samail and Josphine; Nehlig et al., 1994; Harper, 1995; Jowitt et al., 2012). Alt et al. (1998) suggest that the degree of hydrothermal alteration in forearcs is more extensive and occurs at a higher water/rock ratio than at mid-ocean ridges, and is comparable to those observed in SSZ ophiolites. High water/rock ratio (500–1000) is typical for epidosite formation (Alt, 1995). The similarity between modern forearc epidosites and SSZ ophiolite epidosites suggests that the subduction factor plays a significant role in their formation.

As mentioned above, the epidosite formation corresponds with the earliest (ocean-floor) event in metamorphic history of ophiolitic sequences. In the plutonic and subvolcanic/volcanic members of the Mount Ślęża ophiolite the imprint of oceanic stage (strictly on-axis) is locally overprinted to obliterated by Variscan rejuvenation (author's unpublished data). The rejuvenation is connected with a post-orogenic intrusion of Strzegom-Sobótka granitoid (see Turniak et al., 2014 and references therein). The granitoid intrusion produced a narrow (<200 m), zoned contact aureole. The innermost zone of the aureole is marked by the presence of hornblende-plagioclase hornfels with discrete epidote + zoizite + diopside + garnet skarn-like veins. The hornfels gradually transit to greenschist facies (epidote + albite + Cu-Fe sulphides) patchy overprints. Nevertheless, the discovered epidosite suite is located beyond the outermost (greenschist) zone of the contact aureole, and should not be connected with Variscan overprint.

CONCLUDING REMARKS

Epidosites from the Mount Ślęża ophiolite are hosted in a basaltic/andesitic sheeted dyke complex and represent A-type epidosites. Key characteristic of the discovered rock suite is the reduction of phases to a granoblastic association of quartz + epidote + titanite combined with complete replacement of igneous textures and almost complete replacement of the primary mineral assemblage (relics of ilmenite with low $MgTiO_3$ and $MnTiO_3$ component, typical for gabbroic rocks; Haggerty, 1976). The mineral assemblage (i.e. lack of chlorite) and metasomatic texture of the Mount Ślęża ophiolite epidosites are similar to those from Cyprus (Troodos ophiolite) end-member epidosites of the Spillia–Kanavia zone (in terms of Jowitt et al., 2012). The isotope mass-balance of sulphur from basalt/andesite protholite sulphides suggests that the Mount Ślęża ophiolite epidosites interact with sea water derived and magmatic (degassed) fluids at the temperature of about 450°C (Jędrysek et al., 2000). Chemical composition of epidote (Ps_{16} to Ps_{31}) is analogous to other ophiolite-hosted A-type epidosites (i.e. Samail ophiolite; Nehlig et al., 1994). Gabbroic affinity of ilmenite directly points to A-type epidosite. These characteristics point toward their formation at the base of focused upflow zone beneath an active, ore-forming mid-ocean ridge hydrothermal system that vent as a black smokers on the ocean-floor. The presence of epidosite suite in the Mount Ślęża ophiolite can be thus interpreted as a remnant of a feeder zone for at least once present deposit (Cu, Zn and Co). Such a possibility has never been considered as a prospective one for the Central Sudetic Ophiolites (Olszyński et al., 2001; Mikulski, 2012 and references therein), nevertheless, the relations between sulphide mineralisation and volcanic members of ophiolitic complexes were kept in mind (Olszyński et al., 2001; Mikulski, 2004).

The presence of epidosites in SSZ affinity ophiolites, modern subduction-related environments, and their absence in MOR point to a conclusion that tectonic setting is an important factor controlling their formation. According to the above-mentioned structural premise, epidosites can be considered as an evidence of SSZ affinity of the Mount Ślęża ophiolite. The SSZ-related origin of at least part of the ophiolite was proposed by Dubińska and Gunia (1997) and Delura (2012).

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